Effects of temperature and mixing modes on the performance of municipal solid waste anaerobic slurry digester

Azadeh Babaei¹ · Jalal Shayegan¹

Received: 21 April 2019 / Accepted: 3 December 2019 / Published online: 2 January 2020
© Springer Nature Switzerland AG 2020

Abstract

Purpose Anaerobic digestion is a promising technology for simultaneous treatment of biodegradable organic matter of municipal solid waste (MSW) and production of renewable energy. Mixing modes and temperature have influences on biogas production in anaerobic digesters treating MSW. Therefore, in this study, digester was operated at different modes of mixing and temperatures to obtain design criteria.

Methods The experiments were carried out in a semi-continuous digester. In the first part of the investigation, temperature was set at 25, 28, 31 and 34 °C. During this step, digester content was mixed in an intermittent mode by mechanical mixers. In the second part of the study, mixing condition of the digester was set at various modes: continuous, intermittent (15 min on and 30 min off) and minimal (twice in a batch).

Results Digestion with a temperature in this range resulted in biogas yield of 0.23–0.33 m³ biogas/kg VS, with a methane content of 60.2–71.8% in biogas. The methane content and yield decreased with reduction of digestion temperature. However, this reduction was almost negligible from 34 to 31 °C. In addition, in comparison to intermittent mixing, continuous and minimal mixing modes reduced the biogas production by 40% and 50%, respectively. Therefore, in this digester greatest biogas yield of 0.33 ± 0.02 m³ biogas/kg VS were obtained at 34 °C and intermittent mixing mode.

Conclusions Based on the data obtained from this study, temperature in the range of 31–34 °C and intermittent mixing is suggested as a base for design purposes.

Keywords Anaerobic digestion · Biogas · Mesophilic · Mixing · Municipal solid wastes

Introduction

The amount of municipal solid waste (MSW) generated in Iran is around 60,000 ton/day which comprises more than 70% of organic wastes. The easily biodegradable organic matter of MSW such as vegetable waste facilitates its biological treatment. This shows the potential of these wastes for anaerobic digestion [1]. Slurry anaerobic digester is a promising technology for simultaneous treatment of MSW and production of renewable energy (biogas) and fertilizer [2, 3]. Environmental conditions such as pH and temperature, inhibitory parameters such as high ammonia concentration, and the ratio of volatile fatty acids to alkalinity are among the

parameters affecting the efficiency of anaerobic digester. Volatile solids loading rate, temperature and mixing are operational parameters that significantly influence digester performance [4, 5].

Temperature of digester affects the activities of the anaerobic bacteria and waste decomposition. The rate of degradation and biogas production is enhanced at higher temperatures [6]. The optimum digester temperature, considering both the potential biogas yield and heat demand, is one of the most crucial factors for economical operation of digester [7]. Previous researches have suggested that the trend of gas production was linear which was between 0.26 and 0.42 CH₄ m³/kg TS in the temperature range of 25–44 °C [8, 9]. Other researchers reported that the concentration of free ammonia (inhibitor) increased with the rise of temperature, leading to the decrease in biogas yield [10, 11].

Mixing is another important parameter that should be taken into account to achieve optimal anaerobic digestion. It is necessary to apply an appropriate mixing mode in order to

✉ Jalal Shayegan
shayegan@sharif.edu

¹ Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran

maintain the uniformity of environmental factors (substrate concentration, temperature, etc.) as well as prevent scum formation and stratification [4, 12]. Beneficial mixing can be attained with various methods, including mechanical mixers, recirculation of digester contents or produced biogas [13]. The main factors affecting digester mixing are the mixing strategy, intensity and duration. Adequate mixing improves the distribution of substrates and microorganisms throughout the digester [14, 15] whereas inadequate mixing results in stratification and formation of floating layer of solids [4, 7, 16]. In comparison to unmixed digesters, continuous mixing improved biogas production [17]. Opposite results were also reported by several researchers [18, 19]. Nevertheless, intermediate mixing seems to be the most optimal mode for solid waste degradation [19–21].

Although mixing and temperature are important factors in achieving efficient waste degradation, there is no clear insight into the effects of these parameters on anaerobic digestion of MSW. Therefore, there is a need for further research on evaluating the optimum temperature and mixing strategy. In this study, anaerobic digestion of municipal solid wastes was carried out at different modes of mixing: continuous mixing, minimal mixing (twice in a batch, 30 min each time) and intermittent mixing (15 min on and 30 min off). In addition, the effect of different temperatures within mesophilic ranges (25–34 °C) on digestion of MSW was investigated to obtain design criteria for economical anaerobic digesters in Iran.

Materials and methods

Feedstock preparation

Municipal waste was daily collected from five selected routes and screened to remove the coarse contaminants. The waste was then shredded by an ordinary kitchen blender. The initial total solid (TS) content of MSW was 26%, with total volatile solids (VS) of about 85%. The COD/N ratio of MSW is around 22 (Table 1); therefore, no nitrogen was added to the reactor. The anaerobic sludge from the west wastewater treatment plant of Tehran was added as the seed.

Experimental device

The digester experiments were carried out in a semi-continuous plexy glass digester with a liquid volume of 60 l. Figure 1 illustrates the experimental set-up. A plate was placed at the top of the reactor, which supported the mixer, mixer motor, and gas sampler. Sampling valves were located at the top, middle and bottom layer of digester contents. The contents of the reactor were mixed as controlled by a timer, which was activated for 15 min every 45 min. The digester was operated in mesophilic condition (25–34 °C).

Digester operation

The aim of this study was to attain the basic design criteria; mainly biogas yields at different temperatures and mixing modes for a mesophilic MSW digester. For this purpose, semi-continuous experiments were conducted at organic loading rates of 1.4 kg VS/m³.d [22] with a fixed hydraulic retention time of 25 days in all runs. Retention time of 25 days was maintained by feeding 2.4 L of feedstock and removing 2.4 L of effluent daily. The operation conditions of digester are shown in Table 1. In the first part of the investigation, digester temperature was set at 25, 28, 31 and 34 °C. During this operation, reactor content was mixed in an intermittent mode (15 min on and 30 min off) by mechanical mixers. In the second part of the investigation, the mixing condition of the digester was set at various mixing modes: continuous, intermittent and minimal (twice in a batch, 30 min each time). During this operation, reactor was operated at 34 °C. In all runs, steady-state condition was identified when the measured daily biogas production was the same for two or three consecutive days.

Analyses

Daily biogas production was measured using water displacement method. Biogas samples were taken periodically from the gas collection lines and analyzed for methane using gas chromatography (PERICHROM PR2100). The measured biogas volume was adjusted to the volume at standard

Table 1 The operation condition of digester and influent waste characteristics during the semi-continuous experiments

Run No.	Temperature (°C)	Mixing mode	Digester Conditions	Influent waste Concentration (mg/L)
1	25	Intermittent mode	Initial pH = 7.5 ± 0.3	COD = 3000
2	28	Intermittent mode	HRT = SRT = 25 d	Total Nitrogen = 140
3	31	Intermittent mode	OLR = 1.4 kg VS/m ³ .d	Total Phosphorus = 45
4	34	Intermittent mode		
5	34	Continuous		
6	34	Minimal		

Fig. 1 Schematic diagram of anaerobic digestion experimental set-up

temperature (0 °C) and pressure (1 atm). Chemical oxygen demand (COD), total solids (TS), volatile solids (VS), pH, and alkalinity were determined according to the APHA standard [23]. Total nitrogen (TN) was estimated by Kjeldahl method [24]. All analysis tests were conducted in triplicate.

Statistical analysis

Comparison between the treatments was conducted in Sigma Plot 11.0. Statistical analyses were performed for the biogas and methane yield and VS and COD removal results using one-way analysis of variance (ANOVA) ($P < 0.05$). In order to determine which system had a significant difference with others, Holm-Sidak test was conducted for every binary combination of the systems.

Results and discussions

Effect of temperature on biogas production

Based on the results, total gas production was greatest at 34 °C, and a temperature decrease from 34 to 25 °C resulted in a decreased biogas production (40% higher at 34 °C in comparison with 25 °C). Results at 31 and 34 °C were almost similar, but biogas production at these temperatures was much higher compared to that at 25 °C. There was a faster degradation at higher temperatures, as shown in Fig. 2. Biogas production reached its peak value of 44.5 L/d on the 20th day and 40.3 L/d on the 27th day at 34 and 25 °C, respectively. For this reason, the required time to complete the digestion of MSW at 34 °C was lower than that at 25 °C.

Therefore, approximately 20–27 days seems to be the minimum period for optimal digestion of MSW. The biogas composition differed according to digestion temperature, with

methane contents in biogas of 71.8 ± 2.3 , 70.6 ± 1.6 , 62.5 ± 2.8 and $60.2 \pm 1.2\%$ at 34, 31, 28 and 25 °C, respectively, however, these differences were not statistically significant in the range of 31–34 °C.

The changes of methane content were corresponded to the biological biogas-producing phase that depended on pH value. These findings are in agreement with the results of Chae [25] related to the anaerobic digestion of swine manure under mesophilic conditions. pH of the digester liquid and its stability are extremely important parameters, since methanogenesis only proceeds at a high rate when pH is maintained at 7.6–8 [26]. The variation of alkalinity and pH is shown in Fig. 3. It can be seen that the pH values in the digester operated at higher temperatures are higher compared to that operated at lower temperatures. The rate of biogas and methane production declines at pH values below 7.6 at 28 °C. pH of the digester remained steady in the range of 7.6–8.0 at 34 and 31 °C, indicating that the system was well buffered. As a result, the highest value of biogas produced in the range of

Fig. 2 Biogas production versus time at different temperatures in mesophilic range

Fig. 3 Values of pH and alkalinity at various temperatures

31–34 °C. When the temperature was decreased to 28 and 25 °C, the pH value dropped from 7.6 and reached a lower value of 7.2. For this reason, biogas production was reduced.

These results were in agreement with previous results that showed an improvement in biogas production with the increase in temperature [6, 27].

Fig. 4 **a** Biogas and methane yield and **b** VS and COD removal during digestion of MSW with different temperatures at constant mixing modes (intermittent mixing). Error bars represent the standard deviation of three replicate analysis tests. Means represented by the same letter did not differ significantly from each other

Effect of temperature on the performance of anaerobic digestion

One of the main applications of anaerobic digester is to reduce the influent VS. For that reason, it is important to calculate biogas production versus VS removal. Therefore, in this study, the relative biogas and methane yield at different temperatures in the digestion of MSW is calculated and shown in Fig. 4a. The biogas yield was influenced by temperature in the range of 25–34 °C, but it was not linear within the tested range. The difference in methane yield was not obvious between 34 and 31 °C; approximately 90% of the methane produced at 34 °C was still produced at 31 °C. In contrast, the digestion proceeding at a temperature of 25 °C showed only 70% of that at 34 °C.

According to the results, the greatest biogas and methane yield of 0.33 ± 0.02 m³ biogas/kg VS and 0.21 ± 0.01 m³CH₄/kg VS, respectively, were obtained at 34 °C. This value was relatively low compared to the biogas yield achieved (0.41 m³ biogas/kg VS) from organic fraction of MSW at 37 °C in previous studies [28]. This difference might be attributed to the use of pre-stage flushing and micro-aeration to optimize the hydrolysis/acidification process in the reported study [28]. Also, Fruteau de Lacroix et al. [29] reported $0.21\text{--}0.29$ m³ CH₄/kg VS from anaerobic digestion of MSW during 20–55 days. Given a theoretical methane a potential based on proposed equation [30] and reported empirical formula [31], anaerobic digester were expected to generate high methane productions of 0.41 m³ CH₄/kg VS. Therefore, the experimental methane yield achieved 51% of theoretical methane potential. These comparisons suggest that methane yield is not a crucial performance index for distinguishing the efficiency of different anaerobic digestion conditions.

As temperature decreased, VS and COD degradation decreased (Fig. 4b). As a result, the COD concentration in the effluent increased. This indicates that there was higher hydrolysis but less methanogenesis because methanogenic bacteria are sensitive to temperature and pH change and their activities were low at 25 °C. The highest VS degradation value of $86.0 \pm 2.8\%$ was achieved when operating at 34 °C. On the other hand, when temperature decreased to 25 °C, VS removal was reduced to $76.0 \pm 1.5\%$. Comparably, this VS reduction was similar with a previous result reported that VS reduction of 77.1% was obtained with the retention time of 25 days at 25 °C [32].

Balance between energy demands to heat the digester for a higher gas production must be simultaneously considered when determining the optimum operating temperatures. Therefore, considering the net energy recovery, the optimum temperature in this study might be around 30 °C. Furthermore, temperature has a strong effect on the concentration of free ammonia, which is the important

Fig. 5 **a** Biogas production **b** methane production and pH values change during different mixing modes at 34 °C

inhibitor rather than ammonium (NH₄⁺) [33]. Free ammonia concentration increases with the increase in temperature by influencing the equilibrium. In this study, based on the expression of Zhou et al. [34], free average ammonia concentration (It was calculated during stabilization time) was 7.8 ± 2.1 , 18.5 ± 2.8 , 60.6 ± 1.3 and 63.3 ± 3.1 mg/L at 25, 28, 31 and 34 °C, respectively. Free ammonia concentration increased with the increase in temperature (from 25 °C to 31–34 °C) by influencing the equilibrium. Thus, careful consideration is required when increasing the digestion temperature for the purpose of enhancing methane yield due to the simultaneous increase in the ammonia inhibition.

Effect of mixing modes on biogas production

Adequate mixing provides a uniform environment for micro-organism, which is one of the major parameters in obtaining maximum digester efficiency [4]. The biogas production with different mixing modes is presented in Fig. 5a. In comparison with the intermittent mixing, both minimal and continuous mixing modes showed much less biogas production (50% and 40%, respectively) during the same period. The highest biogas production and methane content were achieved when operating at the intermittent mixing mode (41.0 ± 0.9 L/d with $71.8 \pm 2.3\%$ methane). The improved biogas production under intermittent mixing compared to continuous and minimal mixing can be attributed to better solids and biomass retention in the digester. Similar observations were reported by previous studies [19, 35]. Also, in comparison to continuous mixing,

Fig. 6 **a** Biogas and methane yield and **b** VS and COD degradation during digestion of MSW with different mixing modes at 34 °C. Error bars represent the standard deviation of three replicate analysis tests. Means represented by the same letter did not differ significantly from each other

the energy demand of intermittent mixing could be reduced by 12–29% [35]. Dague et al. [36] also reported that shifting from continuous mixing to intermittent mixing resulted in a higher biogas production during the anaerobic digestion.

The increased methane production under minimally mixed conditions was attributed to a better syntrophic association between H_2 producing and H_2 consuming organisms [37, 38]. It is supposed that in a semi-continuous digester, minimal and intermittent mixing might result in slower hydrolysis and fermentation without affecting the syntrophic association [37]. This would therefore allow the syntrophs and methanogens to consume the fermentation products without any volatile fatty acid (VFA) accumulation [38]. High concentrations of VFA during microbial conversion of biodegradable organic contents could inhibit methanogenesis due to the reduction of pH [39, 40]. Evolution of methanomicrobials indicates that intermittent mixing facilitated syntrophic association and that methanomicrobials were preferred by syntrophic partners for the syntrophic propionate-oxidizing bacteria (SPOB) [41].

The data for biogas production rate shows that the continuous mixing mode produced slightly more biogas than the minimal mixing mode, but the corresponding methane content was found to be lower, probably due to reduction of pH, which was observed to be reduced to 6.8 in the case of continuous mixing mode (Fig. 5b). Continuous mixing could increase hydrolysis and result in high VFA concentrations due to the relatively low growth rate of methanogens. The hydrogen producing bacteria are less sensitive to shear than methanogenic bacteria [42]. Accordingly, unlike the biogas production, the methane production under continuously mixed conditions was lower than that under minimally mixed conditions.

Effect of mixing modes on the performance of anaerobic digestion

Mixing modes also affected the biogas and methane yields. The highest methane yield of $0.21 \pm 0.01 \text{ m}^3\text{CH}_4/\text{kg VS}$ was obtained in intermittent mixing compared to the yields

obtained in other mixing modes (Fig. 6a). Biogas yield obtained during periods with intermittent mixing was 30–56% higher than those obtained with continuous and minimal mixing. The improved biogas yield under intermittent mixing compared to other mixing modes can be attributed to better bioflocculation in the reactor. Several studies indicated that an inadequate mixing in low solids digesters resulted in a floating layer of solids [43]. In those studies, mixing level was increased to prevent formation of the solid layer.

In addition, the effluent VS and COD level was generally lower during the periods of intermittent mixing compared to other mixing modes, which indicates that this mixing mode resulted in stratification of the digester content; thus, it minimized VS and COD loss. The highest VS degradation and COD removal value of $86.0 \pm 2.8\%$ and $55 \pm 2.5\%$, respectively, were achieved when operating with intermittent mixing mode (Fig. 6b). Also, COD removal efficiency for the minimal mixing was about 20% higher than the continuous mixing. Ammonium nitrogen levels were approximately the same in all conditions. The results obtained in the present study suggest that the intermittent mixing mode improves the performance of anaerobic digestion of MSW.

Conclusion

Mixing modes and temperature have influences on biogas and methane production in semi-continuous reactors treating MSW. In the mesophilic temperature range, higher temperature enhanced the methane yield. Biogas yields at 31 and 34 °C were similar, but they were quite high compared to that at 25 °C. However, this result does not imply that the higher temperature is necessarily the optimum condition, due to the larger energy requirement at higher digesting temperatures. Among the three mixing modes tested in the experiments, intermittent mixing was found to improve biogas production by 30–40% compared to continuous and minimal mixing. Based on the data obtained from this study, temperature in the range of 31–34 °C and intermittent mixing is suggested as a base for design purposes.

Acknowledgments This work was supported by Iran National Science Foundation (INSF) (Grant number 97001687).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- Bouallagui H, Ben Cheikh R, Marouani L, Hamdi M. Mesophilic biogas production from fruit and vegetable waste in a tubular digester. *Bioresour Technol*. 2003;86:85–9.
- Ratanatamskul C, Manpetch P. Comparative assessment assessment of prototype digester configuration for biogas recovery from anaerobic co-digestion of food waste and rain tree leaf as feedstock. *Int Biodeterior Biodegrad*. 2016;113:367–74.
- Bonmati A, Flotats X, Mateu L, Campos E. Study of thermal hydrolysis as a pretreatment to mesophilic anaerobic digestion of pig slurry. *Water Sci Technol*. 2001;44(4):109–16.
- Kariyama ID, Zhai X, Wu B. Influence of mixing on anaerobic digestion efficiency in stirred tank digesters: a review. *Water Res*. 2018;143:503–17.
- Forster-Cameiro T, Perez M, Romero LI. Anaerobic digestion of municipal solid wastes: Dry thermophilic performance. *Bioresour Technol*. 2008;99:8180–4.
- Mao C, Feng Y, Wang X, Ren G. Review on research achievements of biogas from anaerobic digestion. *Renew Sust Energ Rev*. 2015;45:540–55.
- Zhang C, Su H, Baeyens J, Tan T. Reviewing the anaerobic digestion of food waste for biogas production. *Renew Sust Energ Rev*. 2014;38:383–92.
- Hansen HH, Angelidaki I, Ahring BK. Anaerobic digestion of swine manure: inhibition by ammonia. *Water Res*. 1998;32(1):5–12.
- Hashimoto AG, Varel VH, Chen YR. Ultimate methane yield from beef cattle waste: effects of temperature, reaction constituents, antibiotics and manure. *Agr Wastes*. 1981;3:241–56.
- Hill DT, Taylor SE, Grift TE. Simulation of low temperature anaerobic digestion of dairy and swine manure. *Bioresour Technol*. 2001;78(2):127–31.
- Angelidaki I, Ahring BK. Anaerobic thermophilic digestion of manure at different ammonia loads: effect of temperature. *Water Res*. 1994;28(3):727–31.
- Lindmark J, Thorin E, Fdhila RB, Dahlquist E. Effects of mixing on the result of anaerobic digestion: review. *Renew Sust Energ Rev*. 2014;40:1030–47.
- Karim K, Hoffmann R, Klasson KT, Al-Dahhan MH. Anaerobic digestion of animal waste: waste strength versus impact of mixing. *Bioresour Technol*. 2005;96:1771–81.
- Lindmark J, Eriksson P, Thorin E. The effects of different mixing intensities during anaerobic digestion of the organic fraction of municipal solid waste. *Waste Manag*. 2014;34(8):1391–7.
- Wu B. CFD simulation of gas mixing in anaerobic digesters. *Comput Electron Agric*. 2014;109:278–86.
- Chen T, Chynoweth DP, Biljetina R. Anaerobic digestion of municipal solid waste in a non-mixed solids concentrating digester. *Appl Biochem Biotechnol*. 1990;(24/25):533–44.
- Ho CC, Tan YK. Anaerobic treatment of palm oil mill effluent by tank digesters. *J Chem Technol Biotechnol B*. 1985;35(2):155–64.
- Hoffmann RA, Garcia ML, Veskivar M, Karim K, Al-Dahhan MH, Angenent LT. Effect of shear on performance and microbial ecology of continuously stirred anaerobic digesters treating animal manure. *Biotechnol Bioeng*. 2008;100:38–48.
- Kaparaju P, Buendia I, Ellegaard L, Angelidaki I. Effects of mixing on methane production during thermophilic anaerobic digestion of manure: lab scale and pilot-scale studies. *Bioresour Technol*. 2008;99:4919–28.
- Kress P, Nägele HJ, Oechsner H, Ruile S. Effect of agitation time on nutrient distribution in a full-scale CSTR biogas digesters. *Bioresour Technol*. 2018;247:1–6.
- Wiedemann L, Conti F, Janus T, Sonnleitner M, Zörner W, Goldbrunner M. Mixing in biogas digesters and development of an artificial substrate for laboratory-scale mixing optimization. *Chem Eng Technol*. 2017;40:238–47.
- Babae A, Shayegan J. Effect of organic loading rates (OLR) on production of methane from anaerobic digestion of vegetables waste. In *World renewable energy congress-Sweden*; 8-13 May;

- 2011; Linköping; Sweden (no. 57, pp. 411–417). Linköping University Electronic Press.
23. APHA. Standard methods for the examination of water and wastewater 15ed: APHA American Public Health Association; 2005.
 24. Greenberg AE, Clesceri LS, Eaton AD. Standard methods for the examination of water and wastewater. 18rd ed. AWWA, WPCF: APHA; 1992.
 25. Chae KJ, Jang AM, Yim SK, Kim IS. The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. *Bioresour Technol*. 2008;99(1):1–6.
 26. Yang L, Huang Y, Zhao M, Huang Z, Miao H, Xu Z, et al. Enhancing biogas generation performance from food wastes by high-solids thermophilic anaerobic digestion: effect of pH adjustment. *Int Biodeterior Biodegrad*. 2015;105:153–9.
 27. Babae A, Shayegan J, Roshani A. Anaerobic slurry co-digestion of poultry manure and straw: effect of organic loading and temperature. *J Environ Health Sci Eng*. 2013;11(1):15.
 28. Nguyen PHL, Kuruparan P, Visvanathan C. Anaerobic digestion of municipal solid waste as a treatment prior to landfill. *Bioresour Technol*. 2007;98:380–7.
 29. Fruteau de Lacroix H, Desbois S, Saint-Joly C. Anaerobic digestion of municipal solid organic waste: Valorga full-scale plant in Tilburg, the Netherlands. *Water Sci Technol*. 1997;36(6–7):457–62.
 30. Hidalgo D, Martín-Marroquín JM, Sastre E. Single-phase and two-phase anaerobic co-digestion of residues from the treatment process of waste vegetable oil and pig manure. *Bioenerg Res*. 2014;7(2): 670–80.
 31. Liwarska-Bizukojc E, Ledakowicz S. Stoichiometry of the aerobic biodegradation of the organic fraction of municipal solid waste. *Biodegrad*. 2003;14:51–6.
 32. Castillo MEF, Crisóstomo DE, Arellano VA. Study the operational condition for anaerobic digestion of urban solid waste. *Waste Manag*. 2006;26:546–56.
 33. Hashimoto AG. Ammonia inhibition of methanogenesis from cattle wastes. *Agr Wastes*. 1986;17:241–61.
 34. Zhou Y, Xu Z, Zhao M, Shi W, Huang Z, He D, et al. Construction and evaluation of efficient solid-state anaerobic digestion system via vinegar residue. *Int Biodeterior Biodegrad*. 2018;133:142–50.
 35. Kowalczyk A, Harnisch E, Schwede S, Gerber M, Span R. Different mixing modes for biogas plants using energy crops. *Appl Energy*. 2013;112:465–72.
 36. Dague RR, McKinney RE, Pfeffer JT. Solids retention in anaerobic waste treatment systems. *Water Pollut Control Fed*. 1970;42(2): R29–46.
 37. Stroot PG, McMahon KD, Mackie RI, Raskin L. Anaerobic codigestion of municipal solid waste and biosolids under various mixing conditions-I. Digester performance *Water Res*. 2001;35: 1804–16.
 38. Vavilin VA, Loshina LY, Flotats X, Angelidaki I. Anaerobic digestion of solid material: multi dimensional modeling of continuous flow reactor with non-uniform influent concentration distributions. *Biotechnol Bioeng*. 2007;97(2):354–66.
 39. Dhar H, Kumar P, Kumar S, Mukherjee S, Vaidya AN. Effect of organic loading rate during anaerobic digestion of municipal solid waste. *Bioresour Technol*. 2016;217:56–61.
 40. Palanichamy J, Palani S. Simulation of anaerobic digestion processes using stochastic algorithm. *J Environ Health Sci Eng*. 2014;12(1):121.
 41. McMahon KD, Zheng D, Stams AJM, Boone D, Mackie RI, Raskin L. Methanogenic and syntrophic population dynamics during startup of anaerobic digesters treating municipal solid waste and biosolids. *Biotechnol Bioeng*. 2004;87(7):823–34.
 42. Trad Z, Fontaine JP, Larroche C, Vial C. Multiscale mixing analysis and modeling of biohydrogen production by dark fermentation. *Renew Energy*. 2016;98:264–82.
 43. Stenstrom M, Ng A, Bhunia PK, Abramson S. Anaerobic digestion of municipal solid waste. *J Environ Eng-ASCE*. 1983;109:1148–58.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.